A semi-autonomous sewer surveillance and inspection vehicle

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Abstract

There are millions of kilometres of sewer pipes of varying size and condition. Often, the exact position and state of these sewers is unknown. In order to map the pipe assets accurately, to detect blockage, breakage, erosion, encrustation and in order to plan maintenance or to build fluid models for flow analysis it is necessary to inspect the sewer assets. Man-entry sewers are inspected by the direct intervention of a human operative. Non man-entry sewers are typically inspected using a video camera mounted on a motorised trolley.

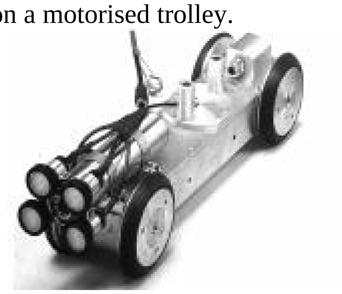

Figure 1. Typical motorised trolley, CCTV, & lights.

In either case, inspection of sewer pipe assets is expensive, time-consuming, subjective, and involves working in an extremely hostile environment. Further, the operatives who perform sewer inspection are responsible for informing maintenance decisions which carry enormous financial consequences. If maintenance is not carried out when it should have been, or vice-versa, substantial costs may be unnecessarily incurred.

City University has developed solutions for the water industry over many years. The work has ranged from: a system to measure pipes of 4 metres in diameter which are used for storm relief (Clarke, 1990); the development of sophisticated image processing techniques for robust pipe joint tracking in long sequences of sewer video (Pan et al, 1994a & b); the development of a instrument for field testing the feasibility of sewer pipe cross-section measurement (Clarke, 1995); to the combined visual and spatial measuring system which is described in this paper. This latest development is a semi-autonomous robotic vehicle equipped with sensor systems and processing power which facilitate high quality sewer inspection by using multi-sensor data acquisition. This enables pipe-modelling and automatic classification of pipe condition. In it's inspection role, the instrument may be deployed to determine the layout and condition of sewer assets. In it's surveillance role, it may be deployed to detect the deterioration of pipe condition under adverse environmental influences such as those caused by adjacent building or tunnelling work. In the event of significant deterioration or damage, these may be quantified in support of compensation claims.

1. Introduction.

The basic sensor system consists a forward-looking CCD camera and a novel cylindrical scanned range camera, the latter employing a laser-based optical triangulation scheme (Clarke et al, 1990b). Processing power is provided by embedded DSP-90 hardware (Gooch et al, 1996) consisting an ADSP2100 family DSP processor board, an IEEE 802.3 Ethernet board, an I/O expansion board, and various peripherals and interface components. The DSP-90 controls the major vehicle systems including the data acquisition and analysis. The entire vehicle is manufactured to flame-proof safety standards, and is highly robust to facilitate the ramming of blockages and obstacles. A practical and a legally mandated safety requirement is that the vehicle is attached to the surface by a cable. Here, the cable carries power and the 10Base2 Ethernet connection. At the surface a van houses the vehicle support electronics which comprise a power supply, a video recorder and display monitor, and a simple PC which controls the Ethernet, video, and data archiving.

The range camera has a working envelope of 70 mm. to 800 mm. to facilitate deployment in pipes of between 150 mm. and 1.2m nominal diameter. Accuracy over this range varies between 60µm and 600µm. The minimum distance measuring time is 50µs/sample which would result in a scanning period of around 10 rev/sec using 2000 range samples/rev. Range data may be used to map the pipe directly, or integrated with data from the video camera. Video data may be processed using Sobel or Canny edge detection schemes, and Hough transform methods can also be used to track the pipe joints (Pan et al, 1994 a&b). The principle throughout is to generate both direct spatial measurement data and image data, which can subsequently feed into the pipe condition classification system.

The incorporation of fast, accurate range camera technology, DSP processing power and Ethernet communications into an intelligent pipe inspection vehicle portends a change in sewer inspection methodologies, elimination of subjectivity in the inspection process, and the cost-effective deployment of comparatively sophisticated equipment in a very down-to-earth industry. This paper describes the system and the experiences resulting from the project. In particular, the range camera technology developed under the project is discussed as having application to a wider range of AGV and mobile robotic applications.

2. Range scanning sensor.

Range camera equipment discussed in this paper is based on the well known principle of optical triangulation. A laser pointer is used to project a target spot on some object of interest. The image of the projected target is then brought to focus on a sensor, and the position of the target image is used to determine the distance of the object from the instrument. Figure 2 illustrates this technique.

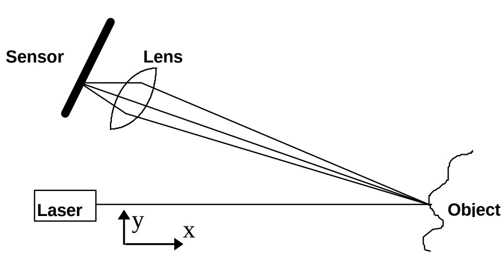

Figure 2. Optical Triangulation.

Typical range camera designs use a fixed baselength optical triangulation sensor together with an actuator which allows the instrument to scan in a 3D scene on a point-by-point basis. Within this paper an instrument is rotated about the 'y' axis (figure 2) in order to scan objects lying in the plane described by the laser beam as it sweeps around. Vehicle motion provides the additional degree of freedom which allows a 3D scene to be surveyed. In advance of a discussion of particular applications, a number of factors relating to the instrument design are now presented.

In consideration of figure 2, it may be seen that the position of the target image on the sensor is related to the range of the projected spot as a function of the angle of the principle ray which emanates from the target and impinges on the lens. Referring to figure 3, some terms are now defined. The baseline is the distance from the laser beam to the centre of the lens, measured normal to the laser beam. The range is $\mathbf{d_{max}}$-$\mathbf{d_{min}}$, where **d** is the distance to the object, measured along the laser beam.

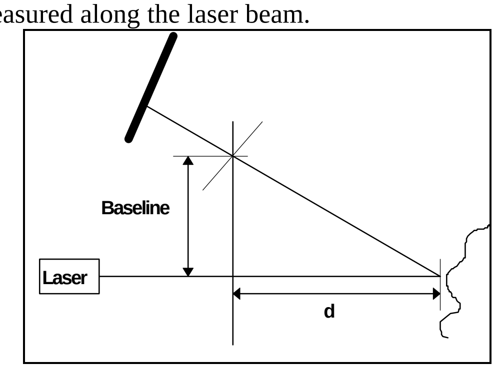

Figure 3. Instrument Design.

In constructing an instrument of the above design, it is usual to employ the Scheimpflug principle (Clarke et al, 1990b) which dictates that for best focusing over the full range, the sensor plane, lens plane, and laser beam must all intersect at a common point. If the lens plane, focal length, baseline, sensor length, and sensor position are all defined, then the resulting range of the instrument is trivial to compute. It turns out that a more interesting problem results if a required range is defined, and the baseline and lens plane angle are to be determined using nominal values for the sensor length and lens focal length. In fact this latter problem is ill-posed. Moreover, if solutions are sought numerically, then alternative results may be encountered. Sometimes no solution is possible. At other times a unique solution, or multiple solutions may be found. Continuation analysis has successfully been employed to determine the loci of feasible solutions in parameter space, and this approach has been integrated into a CAD package to guide the user through the design possibilities and trade-offs that emerge as an instrument specification is gradually refined. Some illustrative case studies are now presented.

• ***Case 1. High speed profiler.*** This instrument was designed with very few pixels in the sensor so that the image could be clocked off the CCD as quickly as possible, thus maximising the sampling rate.

Specification:	dmin	70mm
	dmax	800 mm
	sensor	512 pixels/13µm pitch

Values of baseline for which a solution is possible are plotted against lens focal length (Figure 4).

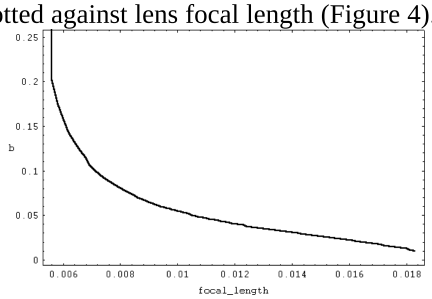

Figure 4. Base line vs focal length.

From this graph, a lens focal length of 8 mm. was selected to give a short baseline. The remaining parameters and performance of the instrument were then determined.

baseline	80.3 mm.
lens field of view	50.8°
pixel resolution at min range	0.185 mm.
pixel resolution at max range	10.81 mm.

Pixel resolution is considered to be the change in distance that is resolved if the image of the target moves by one pixel on the sensor. Although this instrument has a pixel resolution of around 10mm/pixel at the maximum range, the final resolution is increased to at least 1mm/pixel using a sub-pixel algorithm which runs in real-time on the embedded DSP-90 processor. This design is therefore optimised for the highest possible measurement rate. The optical layout is illustrated in figure 5.

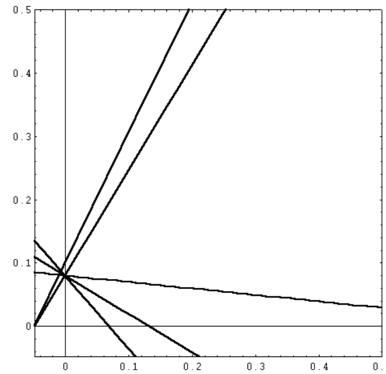

Figure 5. Physical design plot.

• ***Case 2. Vehicle Navigation.*** This instrument is intended for navigation and obstacle avoidance in mobile robotics and autonomous vehicles.

Specification:	dmin	500 mm.
	dmax	5000 mm
	sensor	2048 pixels/13µm pitch

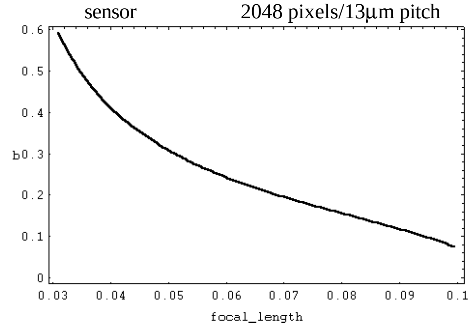

Figure 6. Base line vs focal length.

Here, use of a longer baseline than in the previous design is required in order to keep the lens focal length within reasonable bounds. By choosing a focal length of 60 mm. the remaining parameters were determined.

baseline	233 mm.
lens field of view	34°
pixel resolution at min range	0.213 mm.
pixel resolution at max range	122.5 mm.

Here, resolution of 122 mm./pixel at the maximum range is poor, but often in obstacle avoidance a poor resolution at the far range is acceptable if the near range performance is good. In this case a near range resolution of 0.2 mm. should allow reasonably high precision manoeuvres to be successfully accomplished.

• ***Case 3. High Accuracy Profiler.*** This instrument is intended for slow but high accuracy measurement.

Specification: dmin 90 mm.
dmax 680 mm
sensor 2592 pixels /10µm pitch

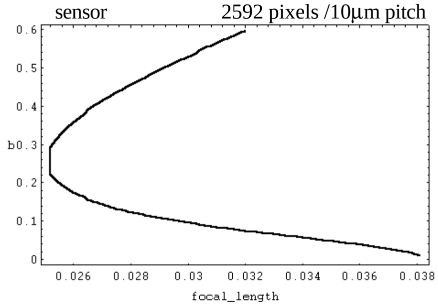

Figure 7. Base line vs focal length.

In this case it is clear that only for lens focal lengths longer than about 32 mm. is a unique solution available. For shorter focal lengths, two alternative solutions are possible. A focal length of 30 mm. was chosen and both solutions computed (Figures 8&9).

baseline	95.7 mm.
lens field of view	42.8°
pixel resolution at min range	0.035 mm.
pixel resolution at max range	1.450 mm.

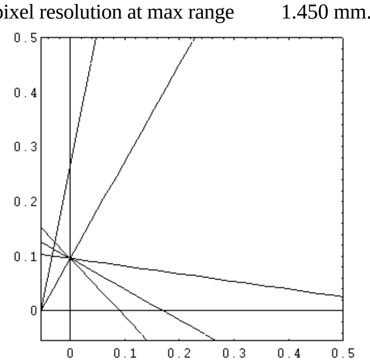

Figure 8. Physical design plot (95.7 mm. baseline).

baseline	529 mm.
lens field of view	68.6°
pixel resolution at min range	0.167 mm.
pixel resolution at max range	0.309 mm.

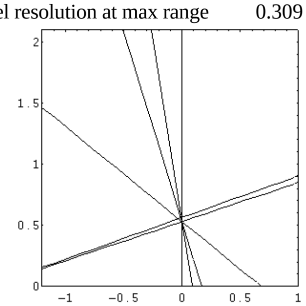

Figure 9. Physical design plot (529 mm. baseline).

The final alternative clearly provides the better overall resolution being almost linear, however it suffers from requiring a relatively long baseline and a very wide angle lens at the focal length required. The latter solution is therefore both impractically large and potentially impossible unless a very high performance lens is available. Hence the former design was the one that was actually built (Clarke, 1995).

3. Target detection & image processing.

Several signal processing and target detection techniques have evolved for use in conjunction with the sensor and vehicle systems described in this paper. In particular, algorithms have been developed for low-level video processing (to extract features and reduce the data bandwidth) and also for analysing, processing and classifying higher level characteristics of the acquired data.

A high performance video processor card has been developed on the DSP-90 standard which provides a configurable interface to a wide variety of linescan and area cameras. The input circuitry provides buffering, sync separation and DC restoration. Ultra-wideband amplifiers are used to achieve 10-bit settling times within the order of 15nS for full-power signals. Image thresholding is performed to reset low level background noise to zero, and a variant of run-length coding of the resulting data stream is implemented in hardware. With high contrast targets based on retro-reflectors or laser pointers, compression ratios of 98% in real-time are typical. Target location and centrioding algorithms have been developed to operate line-by-line on the compressed video data, and typically each DSP-90 system can centroid and track up to 250 targets at the full video frame rate.

In the pipe surveying application, range data may be used to map the pipe directly, or fused with data from the forward looking video camera. This video data may be processed using various edge detection schemes, and Hough transforms are used to track the pipe joints.

Figure 10. Example of two detected and tracked pipe joints.

The principle throughout is to generate both direct measurement data and image data, which subsequently feed into the pipe condition classification system.

4. Further vehicle navigation applications

The first technique uses four CCD cameras to provide a global fix of the robot position within an environment which has retro-reflective targets placed at strategic locations. The proposed system is both fast and relatively cheap. The second technique looks at the problem of obstacle avoidance at close range. In this case a scanning optical triangulation sensor is used to provide both quick obstacle proximity detection and navigation information for cleaning close the same obstacles.

4.1 Global navigation using multiple CCD cameras.

Global navigation will be achieved using a four camera solution and the principle of triangulation. Each camera is able to uniquely identify every target that it can see and provides an estimate of the angle. The position of each camera with respect to the vehicle and its datum are known (Figure 11).

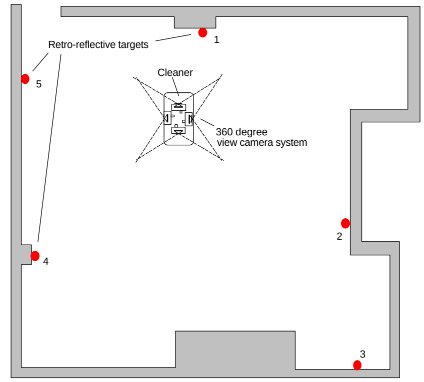

Figure 11. Vehicle and target configuration.

The position of each target is known with respect to a plan of each room. A minimum of two angles are required to define the position and orientation of the cleaner. Each of the cameras is able to resolve angles to better than 1/50 of a degree.

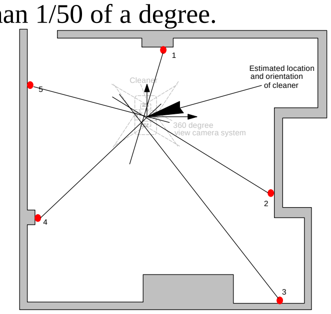

Figure 12. Location and orientation by intersection.

Each angular measurement can be weighted for its distance and an error estimate given for the accuracy of the cleaner location. The accuracy will be dependent on the distance of each target and the level of redundancy employed. If the distance to a given target is 10 metres this is equal to a maximum error of approximately 20 mm. The targets are uniquely identified to the cameras using a vertical code. A simulated view of three sets of coded target patterns is illustrated in figure 13.

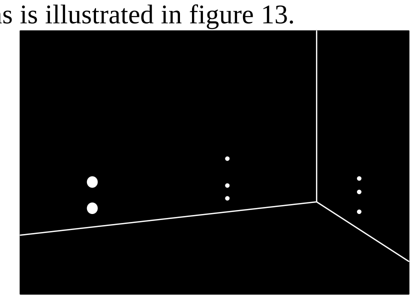

Figure 13. Coded targets.

The targets are made of retro-reflective material and the spacing between the targets provides a unique coding so that each set can be uniquely identified. Noise immunity of the targets is provided by using illumination which is very close to the axis of the cameras.

The four cameras are of the board camera type and are genlocked together. The resolution of the cameras is approximately 500x500. The output of each camera is multiplexed into a video processor board where a single level threshold and proprietary recognition algorithm is able to extract the location of the targets. The four cameras provide a “fix” every 4/25 seconds. The estimation of the location of the vehicle is then relatively simple.

4.2 Object avoidance using a scanning triangulation sensor.

Object avoidance is achieved using a fast sweeping optical triangulation head which provides a scan of any object in the path of the cleaner. The operation is illustrated in figure 14.

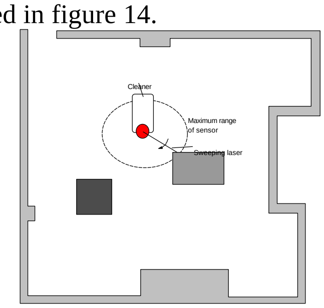

Figure 14. Operation of the scanning head.

The output of the sensor is a number of x,y pairs which describe the object surface with respect to the cleaner itself (figure 15).

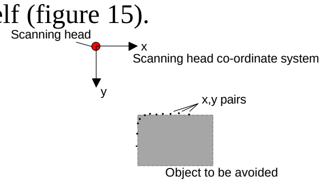

Figure 15. Obstacle avoidance.

Figure 15 illustrates the type of information that would be available from the sensor. The scanner rotates at about five rotations per second will give not only the distance to the point closest to the vehicle but also information concerning the shape of the object. This information can then be used to plan a trajectory to move the vehicle such that it can clean right up to the object. While this process is being conducted the sensor is able to continually monitor the object to check for adequate clearance between the cleaner and the obstacle.

The orientation of the scanning head is not horizontal, as this would only give a single height at which to detect, rather the head is tilted such that the motion of the cleaner provides a 3-D sweep of the object to be cleaned. This is illustrated in figure 16.

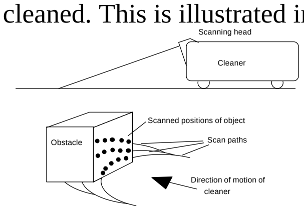

Figure 16. 3-D scanning of obstacles.

5. Conclusion.

This paper has presented an optical triangulation design methodology and some specific examples of instruments for acquiring 2D and 3D range data. The application to sewer pipe profiling has been discussed and opportunities for exploiting the technology in other areas such as robot navigation has been considered.

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6. References.

T.A. Clarke, 1990a ‘The Use of Optical Triangulation for High Speed Acquisition of Cross Sections or Profiles of Structures’ Photogrammetric Record, October, pp 523-532.

T.A Clarke, K.T.V, Grattan, N.E. Lindsey, 1990b. The use of laser based triangulation techniques in optical inspection of industrial structures, Int. Symposium on Optical and Opto-electronic Applied Science and Engineering, Proc SPIE Vol 1332.50.

Clarke, T.A. 1995, The development of an optical triangulation pipe profiling instrument, Optical 3-D Measurement Techniques III. pp 331-340.

R.M. Gooch, T.A. Clarke D.D.A. Pushpakumara & T.J. Ellis ‘Driving a DSP Underground’ Proc. DSP’96, Copenhagen, Denmark 1996.

X. Pan, T.A, Clarke, T.J. Ellis. 1994a, The detection and tracking of pipe joints in noisy images, Videometrics III, SPIE Vol. 2350. Boston. pp. 136-147.

X. Pan, T.J. Ellis & T.A. Clarke 1995, ‘Robust Tracking of Circular Features’ BMVC’95 Proc. British Machine Vision Conference, Vol.2, pp 553-562, 1995.

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